

Heavy Ion Collisions at RHIC and at the LHC: Physics Challenges

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Abstract. Five years after starting operation, the Relativistic Heavy Ion Collider RHIC has finished the discovery stage of its relativistic heavy ion program. Here, I discuss in a simplified way the main discoveries of RHIC and the central open questions, which arise from these results. How can one achieve further progress in studying QCD matter at the highest density in the upcoming era, when both RHIC and LHC will be operational? Rather than listing the richness of the discoveries made at RHIC and expected at the LHC, I try to identify those generic features of a heavy ion program at collider energies, which lie at the basis of further progress.

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INTRODUCTION

Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools? What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons? What is the origin of chiral symmetry breaking?

These questions about chiral symmetry restoration and deconfinement have been central to relativistic heavy ion physics for more than three decades. In the above form, they have been identified as fundamental by the 2002 Long Range Plan (LRP) of the Nuclear Science Advisory Committee [1], which is currently used to assess progress at RHIC. The physics scope of a heavy ion program is broader. For every fundamental theory of nature, it is a central issue to establish how collective phenomena and macroscopic properties of matter arise from the elementary interactions between basic degrees of freedom. For Quantum Chromodynamics (QCD), the fundamental theory of the strong interactions, there are reasons to believe that the properties of primordial QCD matter show a richer and qualitatively different structure than that of primordial QED matter, simply because the theory is based on a non-abelian gauge group and since it displays a change of the elementary degrees of freedom with increasing resolution Q^2 . In accordance with these general considerations, the QCD phase diagram is expected to display at high baryochemical potential a rich phase structure, emerging from the non-abelian analogue of superconductivity [2]. The change of the elementary degrees of freedom is seen at relatively low critical temperature $T > T_c \sim 175$ MeV at $\mu_B = 0$, where primordial QCD matter is predicted to undergo the phase transition to a chirally symmetric, deconfined ground state. This critical temperature corresponds to an energy density, which lies a small factor 3-5 above the energy density of normal nuclear matter, and is thus within reach of laboratory experiments.

The QCD phase transition is the most dramatic manifestation of a collective phenomenon in QCD. But heavy ion physics explores a wide range of other collective phenomena: *In relativistic heavy-ion collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?* This set of questions from the 2002 LRP addresses the dynamics of (possibly incomplete) equilibration processes. Given the short lifetime of the dense matter produced in nucleus-nucleus collisions and its rapid evolution, an understanding of the microscopic mechanisms driving equilibration is of obvious importance, if one wants to study the properties of equilibrium QCD at high temperatures. But rather than being an unwanted complication in the search of the QCD high temperature equilibrium state, I shall argue in the following that the strong collective dynamics observed in relativistic heavy ion collisions provides the very means with which we can study the properties of QCD at extreme densities.

What are the properties of matter at the highest energy densities? Is the basic idea that such matter is best described using fundamental quarks and gluons correct? This is the last of the four fundamental questions identified in the 2002 LRP. In the context of this question, it is worth noting that any discussion of properties of matter is closely related to non-equilibrium physics for the following three reasons: First, theoretically, dissipative properties of matter (such as shear viscosity, bulk viscosity, or heat conductivity) and transport properties of matter (such as the conductivities of conserved charges) characterize the last non-equilibrium stage of an equilibration process, the relaxation into equilibrium. This is so, although the Green-Kubo formula allows us to determine them from spectral functions calculated in the equilibrium state. Second, operationally, the quantitative assessment of non-equilibrium features of a heavy ion collision is a prerequisite for determining an equilibrium state. As I discuss below, the main phenomenological challenge in characterizing properties of the produced matter in heavy ion collisions is to quantify to what extent local equilibrium has been achieved during the collision. Third, it turns out that the processes, which are initially the furthest away from equilibrium, such as jets, provide arguably the widest class of sensitive probes for characterizing the properties of the produced matter (see below). For these three reasons, an alternative title of this talk, aimed at a general audience, could be: 'Heavy Ion Collisions: From Non-Equilibrium to Equilibrium QCD'. The title would indicate not only that RHIC data show evidence of strong equilibration processes, which drive the system into rapid equilibrium. The title would also emphasize that it is the systematic understanding of non-equilibrium processes, which provides the most promising avenue for studying equilibrium QCD at the highest energy densities.

The above-mentioned questions of the 2002 LRP identify a rather narrow, albeit canonical, list of goals of a relativistic heavy ion program. The range of fundamental questions accessible in heavy ion collisions is wider (including e.g. perturbative saturation [3, 4, 5], dynamics of hadronization [6], as well as many more speculative searches). That I do not expand on these important issues here reflects only the page limitation of this article, not the limitation of the field.

WHY COLLIDER ENERGIES?

The issues identified above concern properties of QCD matter, which arise on typical momentum scales comparable to the critical temperature $T_c \sim 150$ MeV of the QCD phase transition, or somewhat higher characteristic medium scales such as the partonic saturation scale $Q_s \sim 1 - 2$ GeV. Why are much higher center of mass energies of $\sqrt{s_{NN}} = 200$ GeV at RHIC or $\sqrt{s_{NN}} = 5500$ GeV at the LHC needed to assess medium properties at these relatively low scales? There are essentially two answers to this elementary question:

First, one expects large quantitative gains for producing and studying sizeable amounts of dense QCD matter at higher center of mass energies. Higher center of mass energies, so the argument, lead to the production of QCD matter at higher initial densities [7]. As a consequence, one either expects a significantly longer lifetime of the produced dense matter and, due to expansion, a larger volume over which this matter is spread. Alternatively, the higher initial density may drive a more explosive dynamical evolution, thereby leading to dense matter of relatively short lifetime, but exhibiting significantly stronger collective effects [8, 9]. In either case, the conditions for studying collective phenomena of QCD matter at the highest density are expected to be improved significantly, either because the increased strength of collective phenomena allows us to study their dynamical origin in much more detail, or because the substantially increased lifetime of the system provides for their manifestation in experimentally more accessible and possibly qualitatively novel ways. This line of argument is consistent with a large set of data on soft hadronic observables at RHIC [10, 11, 12, 13], but it received also significant support from the analysis of fixed target experiments at the CERN SPS [16].

Second, at collider energies, a large number of qualitatively novel, high- Q^2 processes will become newly available for establishing the properties of high-density QCD matter. From the example of Deep Inelastic Scattering, it is well-known that the resolution of high- Q^2 -processes provides unprecedented access to the properties of QCD matter. Clearly, the transient state of hot and dense matter, produced in nucleus-nucleus collisions, cannot be studied with DIS-like external large- Q^2 processes, since its lifetime is much too short. However, at sufficiently high center of mass energy, heavy-ion collisions auto-generate hard probes, i.e., high- Q^2 processes such as jets, which originate inside the dense QCD matter but whose spatial and temporal scales of production $\sim 1/Q$ are much smaller than the typical time and length scales in the medium. As a consequence, one expects that the initial production of these hard probes can be controlled theoretically and experimentally, but that their propagation through and interaction with the dense QCD environment leads to medium-modifications of the hard process. In this way, hard probes are both 'calibrated' and they are sensitive to the properties of the produced matter. To determine their use, the central question is:

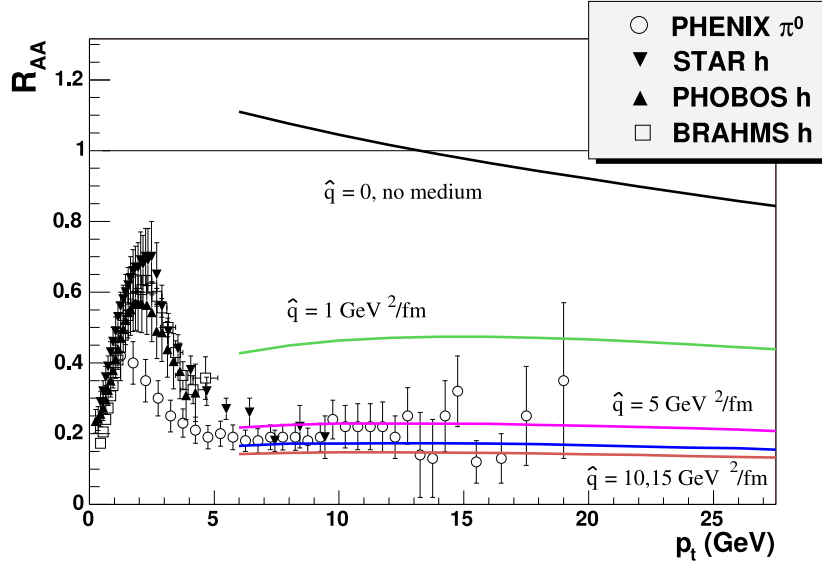


FIGURE 1. Nuclear modification factor R_{AA} for charged hadrons in central AuAu collisions at $\sqrt{s}=200$ GeV [14]. Preliminary PHENIX π^0 -data from Ref. [15].

HOW SENSITIVE ARE HARD PROBES?

Figure 1 shows the nuclear modification factor

$$R_{AA}(p_T, y) = \frac{d^2 N^{AA}/dp_T dy}{N_{\text{coll}} d^2 N^{NN}/dp_T dy}, \quad (1)$$

measured for central $\sqrt{s_{NN}} = 200$ GeV Au-Au collisions at mid-rapidity $y \sim 0$. For all identified hadron species, the single inclusive hadron spectra $d^2 N^{AA}/dp_T dy$ are suppressed at high transverse momentum by the same large factor ~ 5 , if compared to the baseline of an equivalent number N_{coll} of nucleon-nucleon collisions. The above figure is representative of a generic phenomenon: nucleus-nucleus collisions at RHIC have established that dense QCD matter strongly modifies the distribution of particles produced in processes involving large momentum transfers [10, 11, 12, 13]. This is seen not only in the strong suppression of single inclusive high- p_T hadron spectra and in the absence of any suppression of the corresponding photon spectra. It is also seen in the centrality dependence of hadron spectra, in their dependence on the orientation with respect to the reaction plane, as well as in back-to-back two-particle correlations and in the characterization of jet-like structures such as the hadron production associated to high- p_T trigger particles [10, 11, 12, 13].

It is important to note that this medium-induced high- p_T hadron suppression is very large, and that the class of measurements exhibiting it is produced abundantly at collider energies. The size of the effect implies that a detailed dynamical understanding

of the medium-dependence of the observed suppression is possible despite the theoretical uncertainties involved in the description of heavy ion collisions. The abundance of the yields ensures that a detailed and multi-faceted experimental characterization of the medium-dependence of the observed suppression is possible despite the experimental uncertainties involved in analyzing a high-multiplicity environment. It is thus the combination of a large medium-dependent effect and an abundant yield, which makes hard probes suitable for a detailed and controlled characterization of the properties of dense QCD matter [10, 11, 12, 13].

All experimental [10, 11, 12, 13] and theoretical [17, 18, 19, 20] evidence is consistent with the picture that a medium-induced energy degradation of final state partons, produced in high- Q^2 processes, lies at the origin of the observed high- p_T hadron suppression. For example, the theoretical curves shown in Fig. 1 were obtained by supplementing a standard perturbative calculation of hadronic spectra with a model of medium-induced radiative parton energy loss, which depends on the density $\sim \hat{q}$ of the produced matter and the in-medium path length over which the produced parton has to propagate in order to escape the medium. The large size of the density, needed for such models to work, is currently an issue of intense theoretical debate.

There are multiple tests to further substantiate the microscopic dynamics conjectured to underly high- p_T hadron suppression. Due to the different color charge of quarks and gluons, and due to differences in the medium-induced parton branching of massive and massless quarks, leading hadron suppression is expected to show a characteristic dependence on parton identity [21]. This can be studied in particular via the measurement of charmed and beauty mesons, and their semi-leptonic decay products. Moreover, the medium-induced energy degradation of leading partons implies significant enhancements and distortions of the multiplicity distributions in jets and jet-like particle correlations [22, 23, 24, 25]. The study of the hadrochemical composition and transverse momentum distribution of these subleading jet remnants provides yet another wide class of measurements, which add insight to the microscopic dynamics of medium-modified parton fragmentation.

So, why is it of fundamental interest to study the microscopic dynamics underlying high- p_T hadron suppression in heavy ion collisions? Ideally, we would like to have a thermometer, which we can insert in a controlled way into the produced matter. A highly energetic jet is the closest one gets in heavy ion collisions to such a thermometer: it does participate in equilibration processes with the produced matter, but it does not melt or disappear. The high energy of a jet ensures, that the jet structure can be seen above the 'background' of the medium. On the other hand, the internal structure of a jet turns out to be highly fragile in the dense environment of a heavy ion collision (leading hadronic fragments are easily suppressed, associated multiplicity is strongly enhanced), and thus this internal jet structure provides sensitive scales for characterizing the medium.

From these considerations, it is also clear that the 30 times increase in center of mass energy in going from RHIC to LHC will lead to qualitatively novel opportunities in the study of hard probes [26, 27, 28]. There are novel ways of calibrating jet structures (e.g. by tagging the recoiling photons or Z-boson), and there is a more than a factor 10 wider kinematical range in transverse momentum or Q^2 , over which hard probes can be studied. Also, the yields are correspondingly higher. Most importantly, the fact that the high- p_T suppression seen at RHIC remains unweakened up to the highest transverse

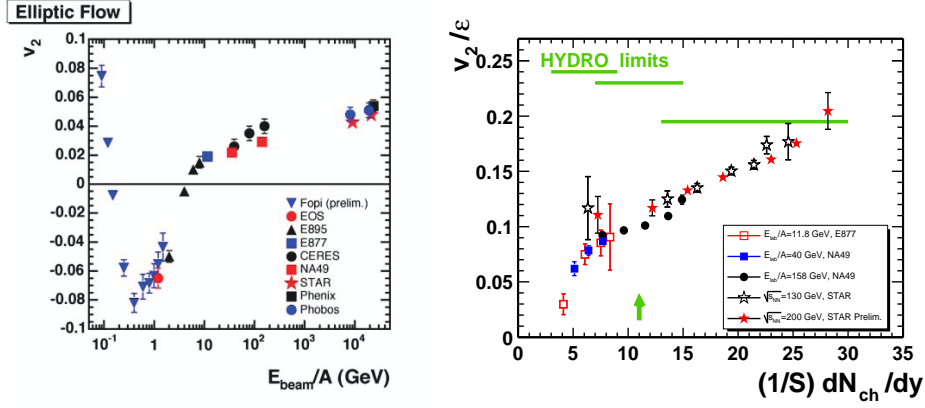


FIGURE 2. Left figure from [29] shows the dependence of elliptic flow on beam energy over 6 orders of magnitude from center of mass energies close to the pion threshold up to the highest collider energies tested so far. The characteristic change of sign of v_2 agrees qualitatively with a hydrodynamic picture. Right figure from [30] shows v_2 scaled to the initial elliptic spatial anisotropy, ϵ , as a function of the charge particle density per unit transverse area. A quantitative agreement with hydrodynamic simulations is only attained at RHIC.

momenta ($p_T \sim 20$ GeV) explored so far, supports expectations that in the kinematically novel, high- p_T regime of the LHC, medium effects will be very large again. Since at higher p_T , a larger component of the jet structure can be accessed relatively cleanly above the soft 'background', this is expected to open many novel opportunities. Here, I have given only a simplified argument, more details and specific proposals can be found e.g. in the CERN Yellow Report on hard probes in heavy ion collisions at the LHC [31, 32, 33, 34]).

CHARACTERIZING COLLECTIVE PHENOMENA

So far, we have argued that the dense QCD matter produced in heavy ion collisions exhibits strong collective phenomena, and that hard probes provide access to the properties of that matter. I now turn to the interplay between hard probes and collective phenomena. The hallmark of a collective phenomenon in heavy ion collisions is 'flow', as measured by the pronounced asymmetry of particle production with respect to the azimuthal orientation $\phi - \Psi_R$ to the reaction plane. The strength of this asymmetry is characterized by the coefficients v_n in the azimuthal composition of single inclusive hadron spectra

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{pd p dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)] \right). \quad (2)$$

In the absence of collective motion, all azimuthal coefficients v_n would vanish. The *qualitative* features of the observed asymmetries are roughly consistent with a hydrodynamic picture of the collision. At low fixed target energies ($E_{\text{beam}} = 2 - 4$ GeV), particle production is enhanced in the direction orthogonal to the reaction plane, and v_2 is negative. This is due to the effect that the spectator parts of the nuclei block the matter in the

direction of the reaction plane and 'squeeze' it out in the opposite direction. At higher center of mass energies, these spectator components free the way sufficiently quickly and particle production is enhanced in the reaction plane. The result is a positive value of the elliptic flow coefficient v_2 , see Fig. 2. This phenomenon is expected in hydrodynamic scenarios in which the larger pressure gradients within the reaction plane drive a stronger expansion.

One of the first discoveries at RHIC was, that the observed asymmetry v_2 continues to grow up to the highest center of mass energies. This indicates that the effective interaction between the partonic constituents of the produced matter increases with increasing $\sqrt{s_{NN}}$. This and the fact that a hydrodynamical description without dissipative corrections can account for the size of the flow is argued to support the notion of a strongly interacting liquid of extremely low viscosity [35]. The statement, that the produced matter at RHIC is a perfect (i.e. dissipation-free) liquid, is very important, since it would imply that the produced matter does not show deviations from local equilibrium. Once the basis of ideal hydrodynamics, namely local equilibrium, is firmly established, hydrodynamics can be used to relate features of the QCD phase transition and the high-temperature phase (such as critical temperature, energy density and equation of state) to measurements. However, as long as dissipative corrections are not constrained quantitatively, the application of an equilibrium picture such as ideal hydrodynamics will always remain questionable, even if its agreement with data is satisfactory.

This raises a significant set of further questions, for instance: Can we measure more detailed manifestations of collective flow in order to further substantiate the picture of a common collective flow field from which different particle species emerge? Can one establish upper and lower bounds on the viscosity of the produced matter, in order to quantify the claim that a perfect liquid has been produced? Can one gain a theoretical understanding of why the viscosity should be very low?

In my view, it is a sign of the increasing maturity of the field of heavy ion physics, that these detailed and complicated questions have received first, still tentative answers in recent years, and that they start to lie within the experimental reach of future experiments. For instance, the picture of a collective flow field implies a strong local position-momentum correlation in the collision region. However, to establish this most elementary manifestation of collective flow requires spatial 'femtoscopic' information, which is very difficult to obtain. The only measurements directly sensitive to position-momentum correlations are two-particle correlation measurements, which are consistent with flow but difficult to interpret [8]. Here, the availability of jets offers novel opportunities. First, the remnants of hard partons, imbedded in a collective flow field, are expected to be blown with this flow. This is a consequence of the fact that parton energy loss is expected to be sensitive to the components of the local energy momentum tensor $T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - pg^{\mu\nu}$; thus, they are sensitive to the flow field u_μ [36, 37, 38]. Characteristic asymmetries in the $\Delta\eta \times \Delta\Phi$ -distribution of jet energy and multiplicity measurements may thus provide independent evidence of collective flow. Second, if the radiated jet energy is really deposited in a non-dissipative, perfect liquid, then it *must* be transported in collective modes along Mach-like cones [39]. However, such Mach-like structures may be faked by recoil effects (see e.g. Ref. [40] for a specific proposal), and it is certainly still too early for a final assessment of the related experimental data [41, 42].

What can be said at the present stage, from my personal point of view, about the statement that the produced matter at RHIC is a liquid with negligible dissipative effects, i.e. a vanishing ratio η/s of viscosity over entropy density? Theoretically, for η/s to be negligible, one requires that the entropy increase throughout the hydrodynamical expansion is negligible compared to the total entropy in the system. This results in a bound $\eta/s \ll \tau T$, which for temperatures and time scales typical in heavy ion collisions is $\eta/s \ll 10$. The most ideal liquid, superfluid helium at 4.3 K, has $\eta/s \sim 9$ [43]. So, the statement that the matter produced at RHIC is a perfect liquid is really a dramatic statement. From the theoretical point of view, there is one remarkable calculation of N=4 super Yang-Mills theory in the strong coupling limit, where in the gravity dual of the theory a very low value $\eta/s = 1/4\pi$ has been calculated rigorously [43]. However, this theory is qualitatively different from QCD (no running coupling, no confinement) and perturbative corrections to the limit are large. The result just illustrates that extremely low dissipative effects may be conceivable. Phenomenologically, a large set of experimental data can be reproduced indeed in hydrodynamical models without dissipative corrections. What is missing, however, is an experimentally established upper and lower bound on η/s . In this sense, the statement about a perfect liquid points to a dramatic possibility consistent with present knowledge, rather than to a firmly established result.

What are the possibilities to further substantiate the claim that the produced matter at RHIC is perfect? We have just started to explore this question. One can state already, that the study of the energy deposition of high- p_T jets is - in principle - sensitive to the dissipative properties of the produced matter (see e.g. the Mach-cone argument given above). It is conceivable that jet measurements can be exploited in the near future to establish a firm upper or even a lower bound on the ratio η/s of viscosity over entropy density. Clearly, this is an ambitious program (which could in the end yield to a number $\eta/s = x \pm y$ for dense QCD matter in the Particle Data Book). This goal, as any attempt to characterize properties of the produced matter with hard probes, will require a detailed microscopic understanding of the mechanisms underlying parton energy loss, in order to disentangle dissipative effects from other dynamical mechanisms. This points again to the general argument, that a better understanding of the properties of dense QCD matter necessitates a better dynamical understanding of the (non-equilibrated) hard probes participating in the onset of equilibration processes, and vice versa. The much wider kinematical range, within which hard probes will be accessible at the LHC can be expected to further enhance dramatically this ability to characterize medium properties with hard probes.

I emphasize again that I have presented here only one of several important lines of arguments, which are currently pursued vigorously. For the last five years, the relativistic heavy ion program at RHIC has provided one of the most active and versatile fields of interplay between theory and experiment of the strong interactions. Rather than illustrating this richness with a large set of examples, it was my purpose to illustrate the most basic equation, on which progress relies in this field:

$$(\text{large medium effects}) + (\text{abundant yields}) = (\text{detailed investigation}).$$

What is accessible with such detailed investigations is truly rewarding: the extension of QCD from a theory of elementary interactions to a theory of collective phenomena, the characterization of fundamental properties of primordial QCD matter at the highest energy densities attainable in the laboratory.

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